Populations of Dwarfs in Clusters of Galaxies: Environmental Connections

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Abstract

Despite their apparent fragile appearance, dwarf spheroidals are the most common galaxy type in clusters. In this paper we consider some of the issues associated with two major models for the origin of these dwarfs: primeval galaxies which formed with the cluster and the modification of accreted systems. We argue that the present observational evidence, derived from the Virgo and Perseus clusters, points to infall as the origin of many of these objects.

1 Introduction

After the advent of high sensitivity photographic emulsions used in combination with wide field telescopes, it became clear that clusters of galaxies contain large numbers of low surface brightness dwarf galaxies (e.g., Binggeli et al. 1985, the Virgo Cluster Catalog (VCC)). These consist predominantly of dwarf elliptical and the structurally similar, but less luminous, dwarf spheroidal systems (hereafter simply 'cluster dEs'; e.g., Caldwell 1987, Impey et al. 1988, Driver et al. 1994, Secker et al. 1997). Although dEs appear to be scaled down ellipticals, they fundamentally differ in some properties such as their mean surface brightnesses within physical radii which scale with luminosity in contrast to the inverse correlation in giant elliptical galaxies (e.g., Wirth & Gallagher 1984, Kormendy 1985, Ferguson & Binggeli 1994).

A revolution in cluster dwarf investigations is now in progress driven by gains from the application of high performance CCD detectors used with cameras and spectrographs. While the fundamental full-coverage photographic studies of the Virgo and Fornax clusters by for example Bingelli et al. (1985) has yet to be equaled, it is clear that clusters of galaxies routinely display rising luminosity functions to $M_V \leq -14$, indicative of huge populations of spheroidal dwarfs. Yet, the origin and evolution of this most common galaxy type remains an intriguing problem. Why are the lowest luminosity density galaxies so numerous in the densest regions of the local universe? Is this a result of galaxy formation processes in regions with above average densities, or could they arise from changes in galaxy evolution induced by interactions within galaxy clusters? We have undertaken a research program, mainly through optical observations with the WIYN 3.5-m telescope to explore these and related issues. The basic results are contained in Conselice (2001) and are reported in more detail in Conselice et al. (2001a,b).

2 Optical Structures of Cluster Dwarf Galaxies

Observations with WFPC2 on the *Hubble Space Telescope*, have recently resolved dEs in the Fornax and Virgo clusters, allowing us to chart their internal properties, especially of their nuclei and

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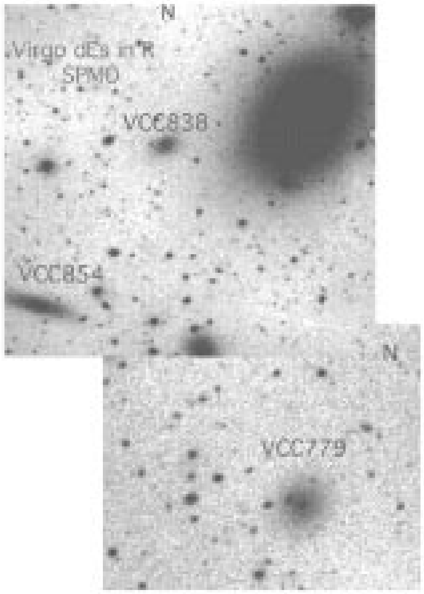

Figure 1 - Dwarf galaxies in the Virgo cluster labeled with their VCC numbers. From deep R-band images obtained by S. Levine with the 2-m telescope at the San Pedro Martir Observatory.

globular star cluster systems (e.g., Miller et al. 1998, O'Neil et al. 1999; Lotz et al. 2001). Figure 1 shows typical dE galaxies in the Virgo cluster. These and similar ground-based observations of nearby galaxy clusters lead to some fundamental descriptions of cluster dEs:

(i) Cluster dEs come in nucleated and non- nucleated varieties, with the frequency of nuclei increasing with luminosity (Sandage & Binggeli 1984, Binggeli & Cameron 1991, Ferguson & Binggeli 1994). WFPC2 observations confirm suspicions of ground-based observers that these nuclei are often offset from the centers of the outer stellar isophotes (cf. Binggeli et al. 2000). Therefore, unlike most spirals, the globular cluster-like nuclei of dEs do not always define the centers of their host systems.

(ii) Cluster dEs have a variety of shapes. This issue has been most thoroughly explored by Ryden et al. (1999) in the Virgo cluster. While a few dwarf S0s were identified by Binggeli et al. (1985), Ryden et al. (1999) found evidence for dEs with both disky (e.g., VCC 854 in Fig. 1; see also Jerjen et al. 2000) and boxy isophotal shapes. The optical structures of cluster dEs are therefore inhomogeneous. At an extreme, some dEs are highly distorted; e.g., near the center of the Coma cluster, presumably due to tidal disruption (Thompson & Gregory 1993).

(iii) While a basic correlation exists between the optical colors and luminosities of cluster dEs, the amount of scatter is large, particularly at low luminosities. Evidently variations exist in the age- metallicity relationships between dEs (Cellone & Forte 1996, Caldwell & Rose 1998, Rakos et al. 2001, Conselice et al. 2001b).

Thus, these observations suggest that cluster dEs do not form a simple population. It is therefore reasonable to consider the possibility that cluster dEs could originate from more than one evolutionary path and in complex ways.

3 Evolution of Cluster Dwarf Populations

In this section we develop a basic description of how the total number of spheroidal dwarfs in a cluster, $N_{dE}(t)$, varies in a simple one spatial zone toy model. In so doing we ignore mass-dependent effects, and any possible non-linearities, as our goal is only to look at mean properties of moderate luminosity dEs with $M_V \leq -14$ mag. If $P_{dE}(t)$ is the production rate of new dE systems at time

t and $D_{dE}(t)$ is the destruction rate, then $\dot{N}_{dE}(t) = P_{dE}(t) - D_{dE}(t)$. If the cluster formed at t_f, then the number of dEs at the current time t_0 is

$$N_{dE}(t_0) = N_{dE}(t_f) + \int_{t_f}^{t_0} \dot{N}_{dE}(t)dt.$$

For a purely primordial cluster dE population we require $P_{dE}(t) = D_{dE}(t) = 0$, which is physically unlikely.

More generally, we could expect that dEs are produced from galaxies infalling into clusters, as in for example the models of Moore et al. (1998; see also Quilis et al. 2000), in which case for an infall rate $\dot{N}_c(t)$ we can write $P_{dE}(t) = c_{dE}(t)\dot{N}_c(t)$ where $c_{dE}(t)$ is the efficiency of conversion of infalling galaxies into dEs, absorbing any time delay into the time variation of the efficiency. The destruction rate should depend on a destruction efficiency $d_{dE}(t)$ such that $D_{dE}(t) = d_{dE}(t)N_{dE}(t)$.

One model is to assume all dEs are made from galaxies that fall into a pre-existing cluster. In this case $N_{dE}(t_f) = 0$, and we can estimate a minimum infall rate by setting $d_{dE}(t) = 0$ for all t. The average infall rate required to make the observed population of dEs in the Virgo cluster, which we adopt as out standard, is then

$$\overline{\dot{N}_c(t)} = N_{dE}(t_0)/\bar{c}_{dE}(t_0 - t_f).$$

To get an a rough estimate of the infall rate, we assume a cluster age of 10 Gyr and a dE production efficiency from all but giant galaxies of 100%. Then since there are $\sim 10^3$ dEs in Virgo, we require an average infall rate of $\geq$100 galaxies per Gyr. High infall rates in the past are therefore necessary, but possible (Kauffmann 1995).

Infall rates are difficult to measure, and likely will be episodic since galaxies may arrive in groups. The number of moderate luminosity galaxies in Virgo that seem to be in an evolutionary transition is not clear, but based on Gallagher & Hunter (1989) it is probably no more than two dozen currently. The lifetime of the transition phases is also uncertain, but from what we now know, it appears that the current infall rate is too low to produce the observed population of dEs and related objects in the Virgo cluster, especially if any destruction occurs and the production efficiency is less than 100%, as is likely.

An alternative perspective is to assume that all dEs were formed when the cluster was young. In this case we need to understand the survival rates of dEs in clusters. Most interactions in clusters occur at high relative velocities, limiting the damage from any one interaction. The impulse approximation then holds and the change in internal energy per collision is given by eq. (7-53) in Binney & Tremaine (1987) with the impact parameter set to the size of a giant elliptical, and hence giving an upper limit on the energy input:

$$\Delta E/E < 7(v_{dE}/v_{rel})^2(\bar{\rho}_{dE}/\bar{\rho}_{giant}).$$

For typical dEs ($v_{dE} \leq 50$ km s^{-1} while relative velocities will be $\sim$1000 km s^{-1}) the fractional change in internal energy per collision is $\Delta E/E < 10^{-3}$ and with only a few collisions per cluster crossing, most dEs will survive collisional heating in a more or less intact state, while more massive galaxies with larger internal velocities will tend to be worn down due to their stronger reactions to collisions. Similarly, the description of tidal disruption by Merritt (1984) shows that most of the stellar bodies of dEs can survive, with only the least massive systems being subject to disruption near cluster cores (cf. Thompson & Gregory 1993, Adami et al. 1998), or around central cluster giant galaxies (López-Cruz et al. 1997).

We conclude that in Virgo, $D_{dE}(t_0)$ is small, and that the infall rate of smaller galaxies exceeds the destruction rate of dEs. The production rate of dEs is less clear due to uncertainties in the astrophysics of converting field galaxies to cluster dEs, but we suspect $P_{dE}(t_0) > D_{dE}(t_0)$ and that therefore the dE population of Virgo is increasing.

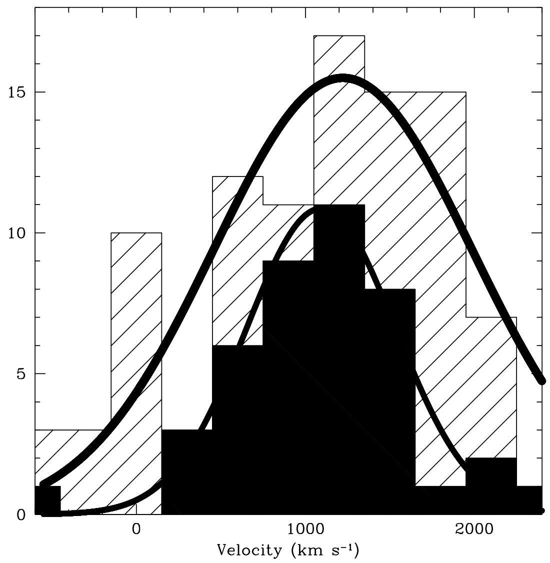

Figure 1: Velocity distribution for the elliptical (solid histograph) and dwarf ellipticals (hatched histograph). Solid lines show the formal Gaussian fits to each distribution.

4 A Kinematic Test of the Infall Model

While the cluster infall model for making dE galaxies has received theoretical and observational support, sharp tests are difficult. Most of the accretion is expected to have occurred several Gyr in the past (Kauffmann 1995), and it is difficult to observe accretion in clusters at that look back time which corresponds to redshifts $z \sim 1$ (but see Martin et al. 2000). One signature of infall would be a range of time scales for the cessation of star formation in dEs, but this is also found in Local Group dEs and dSph, and is challenging to measure in cluster dwarfs due to the effects of the well-known age-metallicity degeneracy on the integrated light of middle age or older stellar populations. We have adopted a third approach for measuring ages: the examination of global kinematics of the Virgo cluster dE population.

A virialized object such as a galaxy cluster grows in density contrast over time with respect to a surrounding expanding universe. Depending on $\Omega_{\rm matter}$ and Ω_λ, the cluster will accrete matter from its surroundings at various rates, with cosmologically expanding matter shells turning around under the influence of gravity (Gunn & Gott 1972; Hamilton 2001). As this process proceeds, the cluster's original core gets buried in a larger system. In principle we then can use the kinematic characteristics of cluster members to define an accretion sequence. Old fully virialized objects will have a peaked, Gaussian-like radial velocity distribution, while objects that now are infalling will have a flat distribution of velocities (Huchra 1985, Schindler et al. 1999). Objects recently acquired by a cluster should lie between these two extremes.

To answer this question we undertook a program to measure radial velocities of Virgo cluster dEs galaxies with the Hydra multi-object fiber system feeding the bench spectrograph on the WIYN Telescope (see Conselice et al. 2001a for details). Combining our new velocities with a larger set from the literature (e.g., Bothun & Mould 1988, Schindler et al. 1999), we found that the dE members of Virgo have intermediate kinematic properties between those of the 'old core' giant elliptical galaxies, and infalling irregular and spiral systems (Figure 2). The velocity distribution of the dEs is significantly wider than that of the E galaxies ($\sigma \approx 730$ km s^{-1} vs. 460 km s^{-1}).

Furthermore, the dEs display more spatial and velocity substructure (Figure 2). The combination of large and substructured velocity and spatial distribution of these dEs, and the fact that the velocity distribution of Virgo dEs is not well fit by a Gaussian and has a ratio with the elliptical galaxies expected for a virialized and accreted component all suggest that dEs are relatively recent additions to the cluster (Conselice et al. 2001a). This also implies that the dEs have an intermediate cluster dynamical age. Thus, many Virgo dEs are not left over from the initial cluster formation.

5 Discussion

Our results lead us to a model where Virgo (and other galaxy cluster) dEs arose from a variety of processes, their spheroidal shapes resulting at least in part from combined effects of gas stripping (Mori & Burkert 2000) and dynamical heating (Moore et al. 1998). The integrated colors of dEs indicate that major star formation typically ceased at least ∼3-5 Gyr in the past. Combining this with the Virgo kinematic results shows that most dEs are likely to be old, but not ancient members of clusters. Thus, a cluster membership age spread probably exists among Virgo dEs. Ferguson and Sandage (1989) noted that the nucleated dEs in Virgo are more centrally concentrated around the giant Es than are the diffuse dEs, which could reflect a difference in age. Unfortunately the kinematic data are not yet sufficient to rigorously check for kinematic differences between the various subclasses of Virgo cluster dEs.

We do not yet know the forms of cluster dEs at birth. The harassment mechanism suggests that moderate mass galaxies, that in the field are small spirals or large irregular galaxies, are good prospects for becoming dEs once they are captured by a galaxy cluster. Sandage and Binggeli (1984) noted that these types of galaxies are common in the field but deficient in galaxy clusters (see also Binggeli et al. 1985); therefore it is possible that cluster versions of these objects have morphologically evolved. Our empirical arguments, and other theoretical models suggest that the galaxy infall rate in clusters peaked about 5-10 Gyr in the past, and this could be when many present-day dEs appeared in the cluster. At these times the conversion of a star-forming disk galaxy into a dE may have been easier since less of a late-type galaxy's baryonic mass would have been converted into stars and thus the effects of gas stripping would have been more dramatic.

If the views presented here prove correct, then dwarf spheroidal galaxies in clusters are substantial products of galaxy evolution rather than primordial 'formation'. This argues against the identification of dE/dSph systems as a class with a first generation of violently star-forming dwarf galaxies, as are expected in some cold dark matter galaxy formation models. We can look forward to eventually resolving this through determinations of the stellar population age and metallicity spreads in cluster and field dEs, an effort that now is under way for nearby systems and can, with 30-m class telescopes operating near their diffraction limit in the near infrared, be extended to the Virgo and Fornax clusters.

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References

Adami, C. et al. 1998, A&A, 334, 765

Binggeli, B. & Cameron, L. M. 1991, A&A, 252, 27

Binggeli, B., Binggeli, B., & Tammann, G.A. 1985, AJ, 90, 395

Binggeli, B., Barazza, F., & Jerjen, H. 2000, A&A, 359, 447

Binney, J., & Tremaine, S. 1987, "Galactic Dynamics", Princeton University Press, Princeton, N.J.

Bothun, G.D., & Mould, J.R. 1988, ApJ, 324, 123

Caldwell, N. 1987, AJ, 94, 1116

Caldwell, N. & Bothun, G. D. 1987, AJ, 94, 1126

Caldwell, N. & Rose, J. A. 1998, AJ, 115, 1423

Cellone, S. A. & Forte, J. C. 1996, ApJ, 461, 176

Conselice, C.J. 2001, PhD Thesis, University of Wisconsin-Madison

Conselice, C.J., Gallagher, J.S., & Wyse, R.F.G. 2001a, ApJ, in press, astro-ph/0105492

Conselice, C.J., Gallagher, J.S., & Wyse, R.F.G. 2001b, in prep.

Driver, S. P., Phillipps, S., Davies, J. L., Morgen, I., & Disney, M. J. 1994, MNRAS, 268, 393

Ferguson, H. C. & Sandage, A. 1989, ApJ, 346, L53

Ferguson, H. C. & Binggeli, B. 1994, A&ARv, 6, 67

Gallagher, J. S. & Hunter, D. A. 1989, AJ, 98, 806

Gunn, J. E. & Gott, III, J. R. 1972, ApJ, 176, 1

Hamilton, A.J.S. 2001, MNRAS, 322, 419

Huchra, J. P. 1985 in The Virgo Cluster, ESO Workshop Proceedings 20, eds. O. G. Richter & B. Binggeli, p.181

Impey, C., Bothun, G. & Malin, D. 1988, ApJ, 330, 634

Jerjen, H., Kalnajs, A., & Binggeli, B. 2000, A&A, 358, 845

Kauffmann, G. 1995, MNRAS, 274, 143

Kormendy, J. 1985, 295, 73

López-Cruz, O., Yee, H. K. C., Brown, J. P., Jones, C., & Forman, W. 1997, ApJ, 475, L97

Lotz, J.M., Telford, R., Ferguson, H.C., Miller, B.W., Stiavelli, M., & Mack, J. 2001, ApJ, 552, 572

Martin, C.L., Lotz, J., & Ferguson, H. C. 2000, ApJ, 543, 97

Merritt, D. 1984, ApJ, 276, 26

Miller, B. W., Lotz, J. M., Ferguson, H. C., Stiavelli, M., & Whitmore, B. C. 1998, ApJ, 508, L133

Moore, B., Lake, G. & Katz, N. 1998, ApJ, 495, 139

Mori, M. & Burkert, A. 2000, ApJ, 538, 559

O'Neil, K., Bothun, G. D., & Impey, C. D. 1999, AJ, 118, 1618 (Erratum 1999, AJ, 119, 984)

Quilis, V., Moore, B., & Bower, R. 2000, Science, 288, 1617

Rakos, K., Schombert, J., Maitzen, H. M., Prugovecki, S., & Odell, A. 2001, AJ, 121. 1974

Ryden, B.S., Terndrup, D.M., Pogge, R.W., & Lauer, T.R. 1999, ApJ, 517, 650

Sandage, A. & Binggeli, B. 1984, AJ, 89, 919

Secker, J., Harris, W.E., & Plummer, J.D. 1997, PASP, 109, 1377

Schindler, S., Binggeli, B., & Bohringer, H. 1999, A&A, 343, 420

Thompson, L. A. & Gregory, S. A. 1993, AJ, 106, 2197

Wirth, A. & Gallagher, J. S. 1984, ApJ, 282, 85